Design and Performance Evaluation of Scheduling Algorithms for Unslotted CSMA/CA with Backoff MAC Protocol in Multiple-Access WDM Ring Networks

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Abstract— **The unslotted *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) with backoff is a fully distributed, asynchronous *Media Access Control* (MAC) protocol for multiple-access *Wavelength Division Multiplexing* (WDM) ring networks with simplicity and robustness comparable to those of Ethernet [1], [2]. In this paper we present the results of performance evaluation of four scheduling algorithms — *Random Select* (RS), *Destination Priority Queueing* (DPQ), *Longest Queue First* (LQF), and *Shortest Packet First* (SPF) — designed for the unslotted CSMA/CA with backoff MAC protocol to address the issues of fairness and bandwidth efficiency. Through extensive network-level simulations for a multiple-access WDM ring with 10 nodes and 10 wavelengths on a 100 km ring, we have verified that under uniform traffic condition, the LQF shows the best performance in terms of throughput and fairness, while for delay, the DPQ shows the best results. We have also identified that the optical buffer size greatly affects the performance of the scheduling algorithms.**

Keywords— **Scheduling, Unslotted CSMA/CA with Backoff, MAC, RS, LQF, DPQ, SPF, WDM, Ring Networks**

I. Introduction

Transmission of *Internet Protocol* (IP) packets over *Wavelength Division Multiplexing* (WDM) layer has been gathering tremendous interest among the optical networking community due to its simplicity and low overhead, resulting from the elimination of intermediate layers like *Asynchronous Transfer Mode* (ATM) and *Synchronous Optical NETwork* (SONET). Among various network architectures available for the IP over WDM, the multiple-access ring is considered one of the most promising and economical network architectures for future optical *Metropolitan Area Networks* (MANs). In the multiple-access ring architecture, it is essential to design *Media Access Control* (MAC) protocols that are efficient in allocating bandwidth with guaranteed fair access to all nodes on the ring.

Unslotted *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) with backoff has been proposed as one of MAC protocols for IP-HORNET — IP version of *Hybrid Optoelectronic Ring NETwork* [1], [2]. The unslotted CSMA/CA with backoff has two unique features as an optical MAC protocol: First, it is a fully distributed, asynchronous protocol that doesn't need a centralized controller or a separate control wavelength to harmonize and synchronize the operations of nodes on a ring. Second, it can naturally support variable length IP packets without complicated segmentation and reassembly, which becomes harder as the line speed of optical wavelengths ever increases.

These features make the unslotted CSMA/CA with backoff MAC protocol very simple and scalable. For actual implementation of the protocol, however, important issues including fairness scheduling and effects of implementation parameters like optical buffer size are to be fully investigated.

Especially, design of fair and efficient scheduling algorithms is critical due to the inherent unfairness in the multiple-access optical ring (or bus) network. Because of unidirectional transmission of signal on the optical ring, the incoming frames from upstream nodes take priority over outgoing frames at a node. Hence, there arises the so-called *positional priority* problem where for a given destination and the corresponding wavelength, access nodes far from the destination node have higher priorities over those closer to destination node. Therefore without proper scheduling that counteracts this unfairness, the experienced quality of service of a connection at a node is highly dependent upon the relative position of the node with respect to its destination. In addition to fairness guarantee, scheduling algorithms should be efficient in use of available bandwidth, which means they should provide good overall throughput.

In this paper we report the design of scheduling algorithms for the unslotted CSMA/CA with backoff MAC protocol to address the issues of fairness and bandwidth efficiency in the multiple-access ring network and the results of performance evaluation through extensive network-level simulations. We also investigate the effect of optical buffer size on the performance of the scheduling algorithms, the buffer size being one of the critical implementation parameters.

The rest of the paper is organized as follows: We first review the unslotted CSMA/CA with backoff MAC protocol in Section II and describe the scheduling algorithms designed in Section III. In Section IV we present simulation results with discussions. Section V summarizes our work.

II. Unslotted CSMA/CA with Backoff MAC Protocol

Carrier sense and collision avoidance operations are depicted in Fig. 1. The access node listens to all wavelengths by monitoring either sub-carriers [1] or baseband optical signals [3], depending on the implementation. When a frame is ready for transmission, the access node checks the occupancy of the target wavelength. If it is free at that instant, the access node begins to transmit the frame. However, since the access node cannot know if the opening is long enough to accommodate the entire frame, it continues to monitor the wavelength. A small 'fixed' optical delay line (*i.e.*, optical buffer) is placed between the point at which the node listens for incoming frames and the point at which the node inserts new frames. This allows the node to terminate its transmission before the frame interferes with the frame already on the ring. If it detects a frame arriving on the same wavelength at its input and the size of optical buffer is not big enough for successful transmission of the remaining frame with a guard band, it immediately interrupts the frame transmission and sends a jamming signal. Otherwise, it can finish the transmission of the entire frame without interruption. Note that the optical buffer size at least should be large enough for transmitting the jamming signal and the guard band before the incoming frame. The jamming signal (like in Ethernet 10/100 Base-T) could be a unique bit pattern, either at baseband or on the sub-carrier. The downstream access node recognizes the incomplete frame by the presence of the jamming signal and pulls it off the ring. The access node can reschedule the transmission of the frame for a later time.

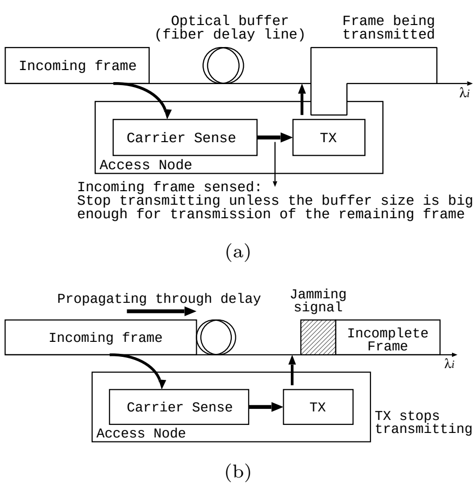

Fig. 1. Unslotted CSMA/CA with backoff: (a) Carrier sense; (b) collision avoidance.

III. Scheduling Algorithms for Unslotted CSMA/CA with Backoff MAC Protocol

A. Random Selection (RS) Scheduling

The MAC implementation has a *Virtual Output Queue* (VOQ) for each wavelength. The RS algorithm maintains a list of empty wavelengths and corresponding "*non-empty*" VOQs. It then randomly selects a VOQ out of the list for transmission. This scheme is fairly simple and has no counter-measure for the unfairness, but we use it as a reference algorithm in performance evaluation of scheduling algorithms.

B. Longest Queue First (LQF) Scheduling

Because of the positional priority, VOQs for those wavelengths whose destinations are closer downstream are likely to have more frames than others. We counteract this problem by giving priorities to those wavelengths with longer VOQs to guarantee fairness. In the LQF scheduling, if wavelengths are available for transmission, the scheduler selects the one with longest VOQ among them.

C. Destination Priority Queueing (DPQ) Scheduling

The DPQ scheduling algorithm tries to achieve the fairness by giving priorities to wavelengths based on their destinations rather than based on the length of VOQs. In this scheduling the wavelengths whose destinations are closer downstream are given higher priorities in order to compensate the effect of the positional priority. Compared to the LQF scheduler, the DPQ scheduler can be more easily implemented because the DPQ uses only destination information of wavelengths in scheduling, which does not change once a network topology is fixed, while the LQF resorts to VOQ length that is continuously changing at each scheduling instant.

D. Shortest Packet First (SPF) Scheduling

While the fairness guarantee is the number one priority in designing the LQF and the DPQ scheduling algorithms, in the SPF scheduling we are trying to maximize bandwidth efficiency by giving priority to wavelengths that have shorter frames in the VOQs. The rationale behind the SPF algorithm is that by sending shorter frames first, it would be possible to reduce the chance of being interrupted by incoming frames.

IV. Performance Evaluation of Scheduling Algorithms

A. Simulation Model and Operational Assumptions

We have developed simulation models for the performance evaluation of the scheduling algorithms based on *Objective Modular Network Testbed in C++* (OMNeT++) [4]. The OMNeT++ is a discrete-event-driven simulator based on C++ and supports models of hierarchically nested modules with multiple links between them, which is an essential feature for the simulation of WDM systems.

The simulation model is for a multiple-access ring network with HORNET architecture, consisting of 10 access nodes with 10 wavelengths on a 100 km ring, where each node on the ring receives frames through a fixed wavelength, but can send frames any wavelengths available through a tunable laser. IP packets are generated with packet size distribution matching that of a measurement trace from one of MCI's backbone OC-3 links [5] and uniform destination distribution. Although the packet generator can generate packets based on either Poisson process or *Interrupted Poisson Process* (IPP), we report only the results based on Poisson process due to space-limit in this paper.

The MAC parameters used are summarized in Table I.[1] Note that the optical buffer size of 13 octets corresponds to the minimum required for the transmission of interrupted frame, while 78, 590, and 1538 octets are the buffer sizes for successful transmission of frames with size up to 66, 578, and 1526 octets, respectively, in the worst case that an incoming frame is detected just after the beginning of frame transmission. These are the frame sizes for the popular IP packet sizes: 40, 552, and 1500 octets.

TABLE I
Unslotted CSMA/CA with Backoff MAC parameters.

Parameter	Value
Line Speed	10 Gbps
Overhead	26 octets
Guard Band	12 octets (=9.6 ns)
Jamming Signal	1 octet
Optical Buffer Size	13, 78, 590, 1538 octets
VOQ Size	1e5 octets

The following performance measures are used: (1) Throughput per node, (2) fairness index [6], and (3) average end-to-end packet delay. Throughput per node is defined as total number of bits delivered during the simulation divided by the product of simulation time and the number of nodes. The fairness index is used to better quantify the fairness of each scheduling algorithm and based on the throughput of all the connections on the network.

B. Simulation Results

We show simulation results of the scheduling algorithms for optical buffer sizes of 13, 78, 590, and 1538 octets in Figs. 2, 3, 4, and 5, respectively.

The maximum achievable throughput is less than the link capacity because the presence of incomplete frames on the ring constitutes wasted bandwidth as described in [1]. As shown in the figures, the difference in maximum achievable throughput per node among the scheduling algorithms is not significant, less than 1 Gbps. However, the fairness index and the end-to-end packet delay show the clear difference among the scheduling algorithms except for the results shown in Fig. 5 where all the algorithms show similar performances. In general the LQF shows the best results with a right balance between throughput and fairness, but it comes at the expense of relatively higher packet delay, for which the DPQ is the best.

From the results, we also identify that the optical buffer size greatly affects the performance of scheduling algorithms, especially at a higher traffic region with larger than 4 Gbps/node of arrival rate, and that the effect of the optical buffer size is larger for non-random schedulers (DPQ, LQF, SPF) than random scheduler (RS). Of the buffer sizes considered, 590 octets shows the best performance because compared to the smaller buffer sizes, it increases the chance of finishing remaining frame transmission when an incoming frame is detected. With even larger buffer size (*i.e.*, 1538 octets), however, performance begins to decrease because the wasted bandwidth by large gaps in the optical buffer compensates for the aforementioned effect. Also, as traffic increases, since it's extremely hard for wavelengths with lower positional priority to get selected by schedulers, performance difference among the scheduling algorithms becomes negligible. Note that, however, these results strongly depend on packet size distribution and the operational assumption we take for handling optical buffer status. For example, if we keep track of all incoming frames in the optical buffer and use openings between them for frame transmission, the performance would improve as the buffer size increases. But this highly increases the implementation complexity, which eventually eliminates the benefits of the unslotted CSMA/CA with backoff MAC protocol.

[1] We adopt parameters from 10 Gigabit Ethernet for frame format (overhead) and interframe gap time (guard band) due to its similarity to the unslotted CSMA/CA with backoff MAC protocol.

V. Summary

In this paper we have described four scheduling algorithms designed for the unslotted CSMA/CA with backoff MAC protocol and presented the results of the performance evaluation through extensive network-level simulations. From the simulation results, we have verified that in general the LQF shows the best performance in terms of throughput and fairness under uniform traffic condition, while for packet delay, the DPQ shows the best results. We have also identified that the optical buffer size greatly affects the performance of the scheduling algorithms, which depends on packet size distribution and the operational assumptions on the optical buffer handling.

Acknowledgments

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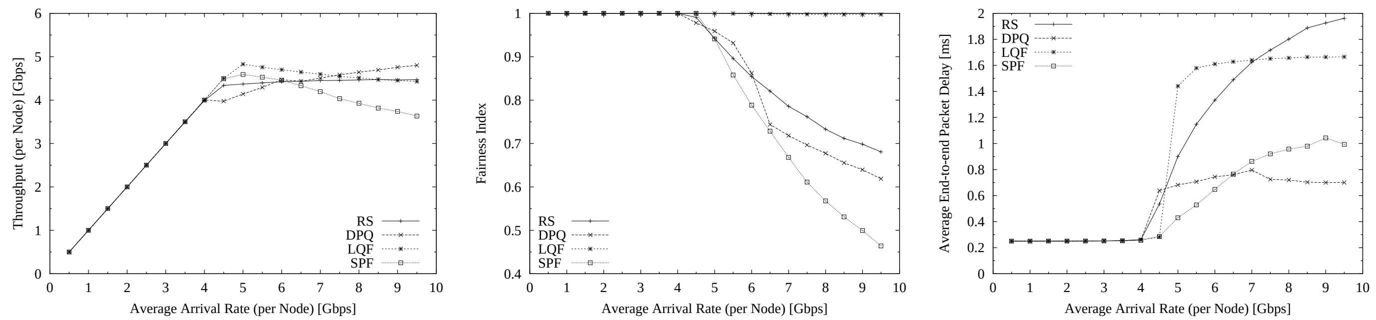
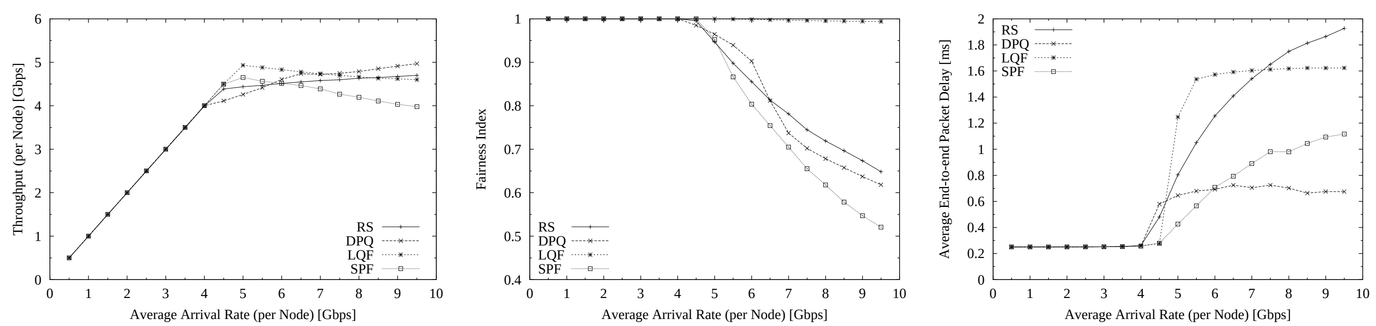


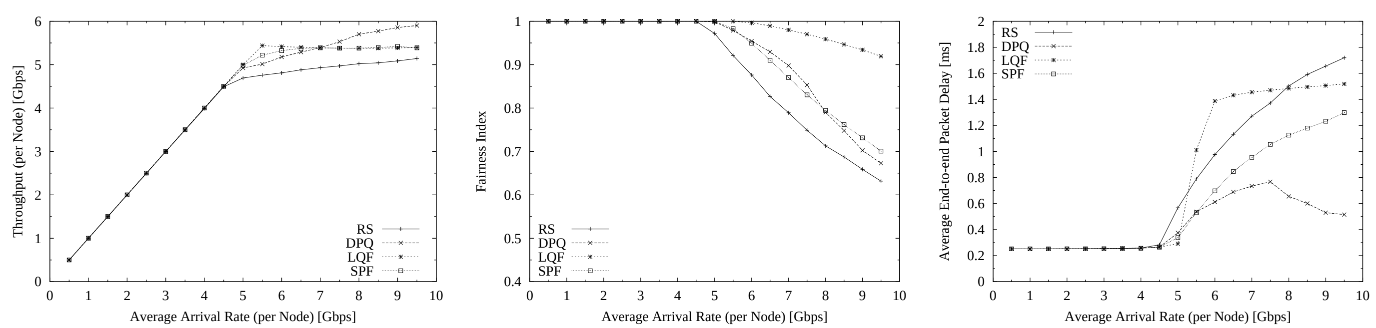
(a) (b) (c)

Fig. 2. Performance of designed scheduling algorithms for optical buffer size of 13 octets: (a) Throughput per node, (b) fairness index, and (c) packet end-to-end delay.



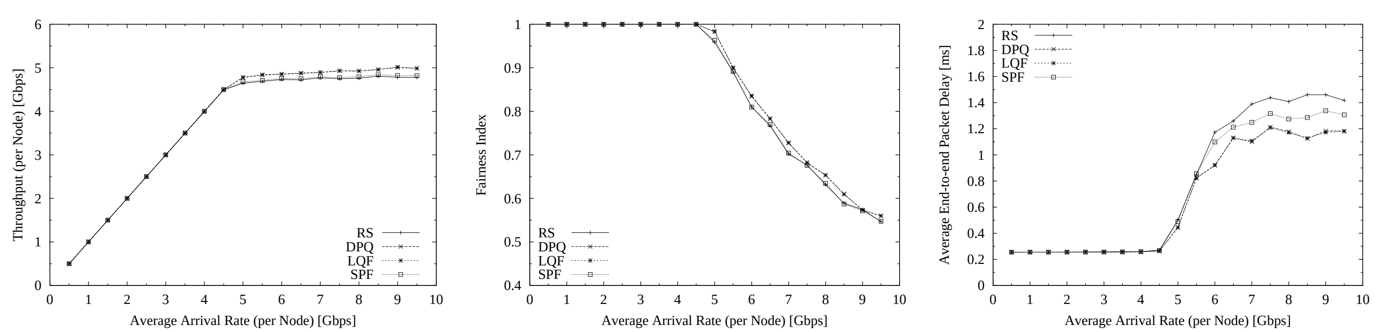
(a) (b) (c)

Fig. 3. Performance of designed scheduling algorithms for optical buffer size of 78 octets: (a) Throughput per node, (b) fairness index, and (c) packet end-to-end delay.



(a) (b) (c)

Fig. 4. Performance of designed scheduling algorithms for optical buffer size of 590 octets: (a) Throughput per node, (b) fairness index, and (c) packet end-to-end delay.



(a) (b) (c)

Fig. 5. Performance of designed scheduling algorithms for optical buffer size of 1538 octets: (a) Throughput per node, (b) fairness index, and (c) packet end-to-end delay.